ISSN 1412-2782 eISSN 2407-9103
Vol 23. No. 2 Mei 2024

Jurnal POLI-TEKNOLOGI

Pile Cap Design Using the Strut and Tie Model (STM) Method

Annisa Wijaya, Sukarman*
Civil Engineering Department, Politeknik Negeri Jakarta, Jl. Prof. DR. G.A. Siwabessy, Kukusan, Kecamatan Beji, Kota Depok, Jawa Barat, Indonesia
*email of corresponding author: sukarman@sipil.pnj.ac.id

Abstract

The design of the pile cap structure generally involves a conventional method that assumes that all areas are linear. The reality distribution strain in cross-section structure pile cap experiences non-linear strain. So it is necessary method close the analysis behavior pile cap actually, that is with the method Strut and Tie Model referring to SNI 2847:2019. Therefore, done study with the formulation problem How designing a reinforcement pile cap with three poles with the method Strut and Tie Model as a comparison configuration reinforcement and requirements material with method conventional. Research methods are done with stages studies literature, data collection, modeling form strut and tie, analysis calculation, up to detailed drawing of the reinforcement pile cap. Comparison configuration reinforcement flexible on method Strut and Tie Model follow the modeling lines element tie, whereas method was conventionally installed with spread reinforcement evenly throughout area pile cap. The strut and Tie Model Method consists of elements 1 (3D16), elements 2 and 3 (4D16) with a total length of reinforcement bending of 18884 mm. The method conventional consists of X direction (6D16) and Y direction (6D16) with a total length of reinforcement bending of 16530 mm. This matter proves that the strut and tie model produces more lots that need reinforcement amounting to 14.24%.

Article History
Submitted: 28/08/2023
Revised : 26/06/2024
Accepted : 16/08/2024
Published: 31/05/2024

Keywords:
Pile Cap,
Three Piles,
Strut and Tie Model,
SNI 287-2019,
Flexural Reinforcement

Introduction

Pile cap is one of the structural elements whose function is to distribute the load from one or more columns to the piles to be forwarded into the ground [1]. The large role of the pile cap in distributing loads requires safe planning to avoid structural failure [2]. Every structural design basically needs to ensure safety under the worst loading conditions and during normal working conditions the deformation of the structural parts does not reduce the shape, durability, and appearance of the structure [3].

The design of pile cap structures generally uses conventional methods that assume all regions experience linear strain. The conventional method uses the Bernoulli hypothesis which in reality cannot be used in the D-region or disturbed area [4]. The strain distribution in the cross-section of the pile cap structure experiences non-linear strain. So an analysis method that approaches the actual behavior of the pile cap is needed, namely the strut and tie model method [5]. The development of ongoing research proves that the strut and tie model method is quite consistent and rational [6].

The strut and tie model was first introduced by Ritter (1899) and Morsch (1902) which originated from the concept of truss analogy. In 2002, ACI 318-2002 was published which discusses the strut and tie model in appendix A. Until June 2019, updated ACI 318: 2019 in chapter 23. Indonesia established this method by adapting ACI to SNI 2847-2013 Appendix A. Until it was updated again in SNI 2847: 2019 regarding structural concrete requirements for building buildings in chapter 23 Strut and Tie Model [7].

In research [8], the STM method for pile cap flexural reinforcement resulted in more reinforcement than the conventional method. The reinforcement is distributed in the band and shear reinforcement is not taken into account. In this method, the designer is required to understand the flow of forces that occur from action to reaction or structural support in modeling a concrete to obtain special reinforcement details [9]. The main elements in the balance of the truss of the strut and tie model method, namely compression rods, tensile rods, node points, fan action, and diagonal pressure fields [10].

Theory

A. Pile Cap

Based on SNI 2847:2019 article 13.4.2.1, the minimum effective height of the pile cap is not less than 300 mm [11]. The designed pile cap must fulfill one-way and two-way shear. There are two general approaches in designing a pile cap, the first is pile cap is designed for shear at the critical section which is considered a high beam. The second method, the Strut and Tie Model [12] is used in designing regions that include D-regions or discontinuities. Discontinuities occur due to changes in cross-sectional dimensions such as openings or changes in forces such as pedestal reactions, large concentrated loads, and post-tensile anchorage zones [13]. At [14] summarizes the geometric shapes for pile arrays in Figure 1.

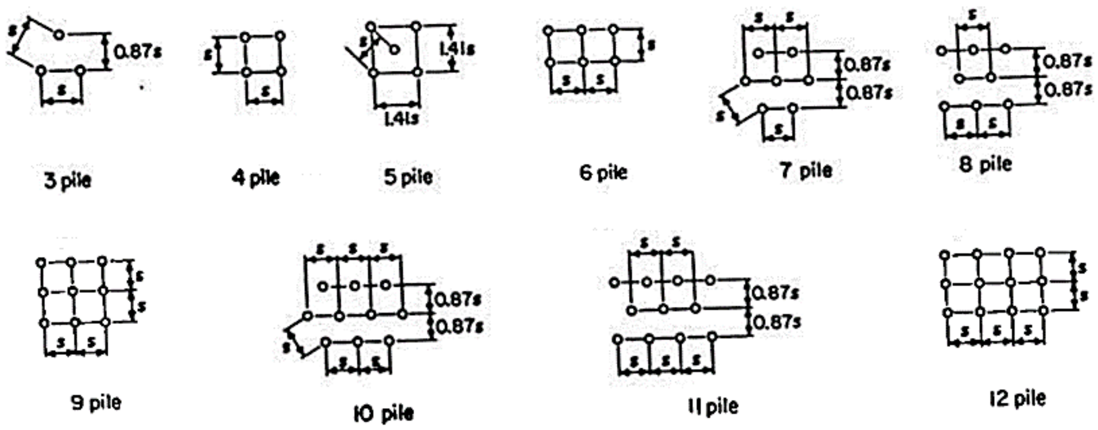

Figure 1: Pile Arrangement Pattern [14]

B. Strut and Tie Model (STM)

The strut and tie model was first introduced by Ritter (1899) and Morsch (1902) which originated from the concept of truss analogy. A reinforced concrete beam structure loaded with P experiences a crack pattern but the force transfer is not direct to the support. Therefore, modeling of compressive and tensile force flow was refined into a truss model . Diagonal compressive bars at an angle of 45° with tensile bars that adjust the stirrup plan (90° or 30° to 45°) [10].

When compiling the strut and tie model several items must be determined, namely the geometric layout of the strut and tie model, strut shape and strength, node zone strength, tie layout and strength, and detail requirements [15]. Research [16] concluded that the success of the strut and tie model method is appropriate for pile cap design. The tested pile cap had a shear to depth span ratio of 0.49 to 1.8 with concrete strength less than 41 MPa.

The design process of the strut and tie model includes 4 steps [11] a) locate and separate each D-region; b) calculate the resultant force at each D-region boundary; c) select the model and calculate the strength in the strut and tie to transfer the resultant force across the D-region; design the strut, tie, and node zones so that they have sufficient strength.

Strut checks can be performed using equations 1 and 2:

$$f_{ns} = f_{ce} A_{cs} \quad (1)$$

$$\phi f_{ns} \geq f_{us} \quad (2)$$

Tie checks can be performed using equations 3 and 4:

$$\phi f_{ns} \geq f_{ut} \quad (3)$$

$$A_{ts} \geq \frac{f_{ut}}{\phi f_{ns}} \quad (4)$$

Metode

In general, the steps taken during the research process can be seen in Figure 2. Modeling the size of the pile cap is done by experimenting as in the research [17] which concluded that the longer the distance between piles, the larger the pile cap area, and the smaller the pile cap thickness. Strut and Tie modeling is done by connecting the column load with the center point of the pile through an inclined strut. The height of the truss is determined in such a way that the angle formed is $\Theta > 25°$. Next, the internal force analysis is carried out with the help of SAP2000 software, then the strength of strut, tie, and node components is checked. After that, calculating and configuring the reinforcement in the pile cap and interpreting the results.

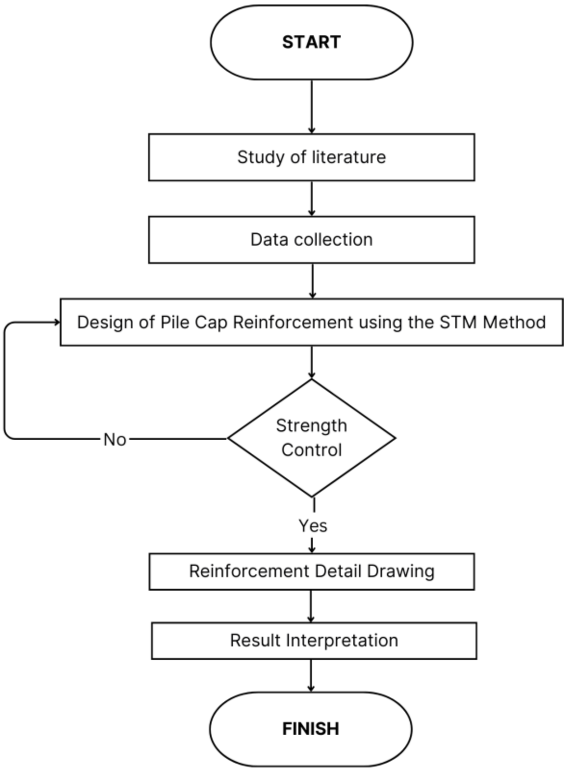

Figure 2: Reaserch Flow Chart

Results and Discussion

A. One-way Shear Control

One-way shear control is performed to ensure that the element can withstand shear forces acting parallel to the length of the element. The shaded area in Figure 3 shows the shear region in detail.

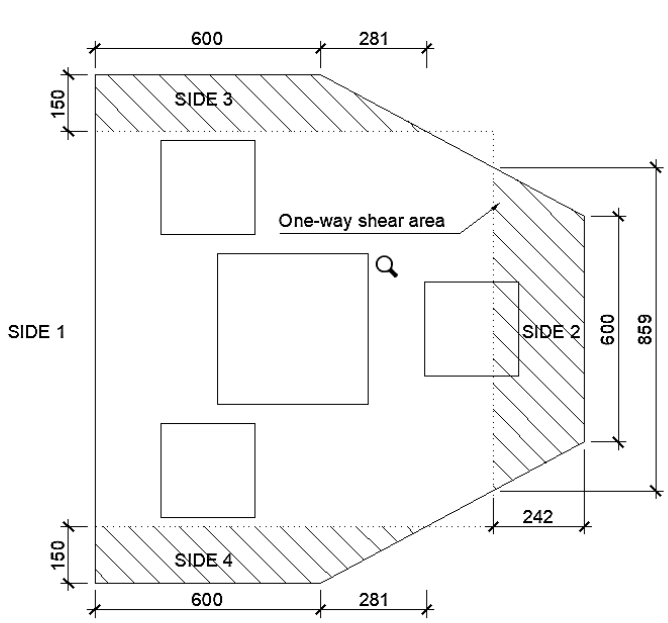

Figure 3: One-way Shear Area

Furthermore, the results of the one-way shear control are presented in Table 1.

TABLE I. ONE-WAY SHEAR CONTROL RESULTS

Vu (ton)		**Vc (ton)**	
Vu 1	0.00	Vc x	27.90
Vu 2	9.32		
Vu 3	5.86	Vc y	26.86
Vu 4	6.86		

Referring to Table 1, the results of one-way shear control in both the x-axis and y-axis directions show that the nominal shear value (Vc) is much greater than the shear value (Vu). So the structural element is safe against one-way shear conditions.

B. Column Two-Way Shear Control

The bidirectional shear control of the column is carried out with the aim of ensuring that the column can withstand shear forces acting from different directions. The shaded area in Figure 4 shows the shear region in detail.

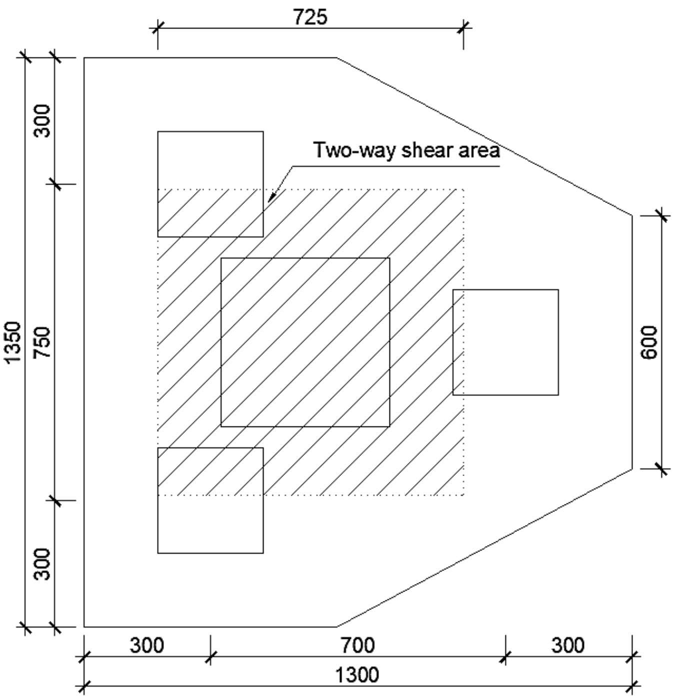

Figure 4: Two-Way Shear Control of Column

Based on the shaded area in Figure 4, it is found that the nominal shear value (Vc = 158.21 tons) is much greater than the applied shear value (Vu = 51.1 tons). Therefore, the structural element is safe against two-way column shear conditions.

C. Two-way Shear Control of Poles

The two-way shear control of the piles was carried out to ensure that the piles could withstand shear forces acting from different directions. The shaded area in Figure 5 shows the shear region in detail.

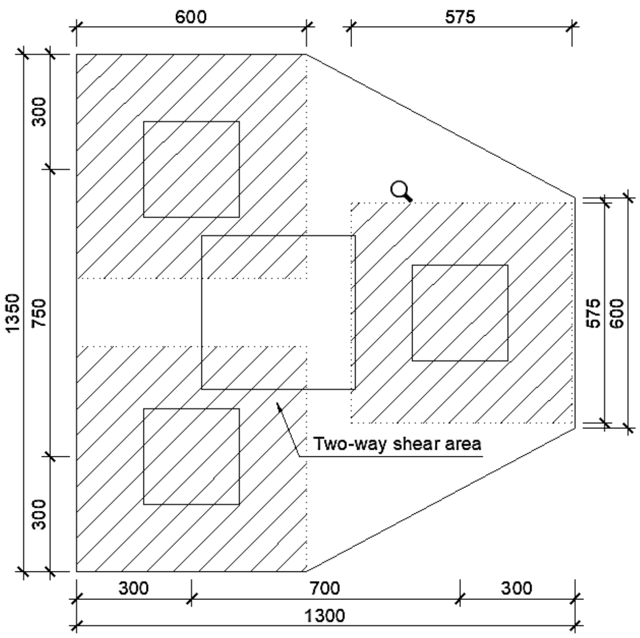

Figure 5: Two-way Shear Region of the Pole

ISSN 1412-2782 eISSN 2407-9103
Vol 23. No. 2 Mei 2024

Based on the shaded area in Figure 5, it is found that the nominal shear value (Vc = 125.47 tons) is much greater than the applied shear value (Vu = 61.37 tons). Therefore, the structural element is safe against the two-way shear condition of the piles.

D. Punching Shear

Shear punching in pile cap foundation analysis is a critical step to ensure that the foundation is able to withstand high concentrations of forces around the pile or column. It prevents local failure, ensures structural safety, meets design standards, avoids costly repairs, optimizes material usage, and increases structural durability. The shaded area in Figure 6 indicates the area of possible shear.

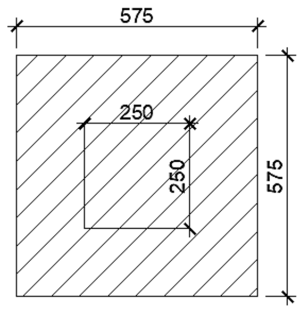

Figure 6: Punching Shear Cap Area of Column

Referring to Figure 6, it was found that the nominal shear value (Vc = 5595.03 tons) is much greater than the applied shear value (Vu = 257.79 tons). Therefore, the structural element is safe against punching shear conditions.

E. STM Shape Modeling and Internal Force Analysis

The modeling of the strut and tie shape of the foundation cap is designed as shown in Figure 7. The angle θ (*strut* inclination) must have a value greater than 25º. The strut and tie form is modeled in SAP2000 with 3 joints divided, each of which is given a loading of P = 257.79 kN with a joint support.

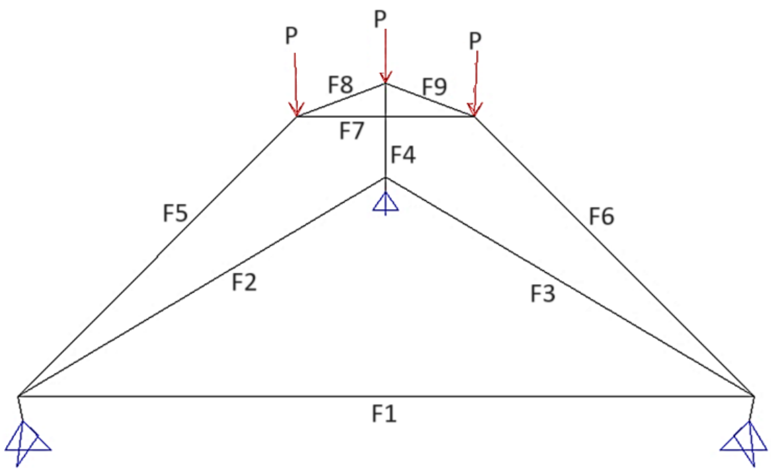

Figure 7: Modeling of Strut and Tie Shape on Foundation Cap

The normal force output in red is negative indicating the element is strut type and green is positive indicating the element is tie type with the values shown in Table 2.

TABLE II. AXIAL FORCES IN THE MODEL

Element	Force (kN)	Type	Description
F_1	189,15	*Tie*	*Tensile*
F_2	200,01	*Tie*	*Tensile*
F_3	200,01	*Tie*	*Tensile*
F_4	436,83	*Strut*	*Compression*
F_5	421,85	*Strut*	*Compression*
F_6	421,85	*Strut*	*Compression*
F_7	189,69	*Strut*	*Compression*
F_8	199,76	*Strut*	*Compression*
F_9	199,76	*Strut*	*Compression*

It is known that elements F_1, F_2, and F_3 belong to the *tie* type, while F_4, F_5, F_6, F_7, F_8, and F_9 belong to the *strut* type. This normal force will be the value of $\mathbf{F_{us}}$ as the factored force acting in the *strut* and $\mathbf{F_{ut}}$ as the factored force acting in the *tie*. Furthermore, the strength control of the *strut* and node zone is carried out to obtain flexural reinforcement.

F. Strut Strength Control of Node

Strut, tie and node control of pile cap foundations is an important aspect in the design and analysis of reinforced concrete structures. This approach is used to ensure that the pile cap can safely resist and transmit forces from the column to the element below. In the STM model (Figure 8) there are two types of nodes, CCC and CTT. So in the process of calculating or controlling the strut strength, two controls are carried out with the help of Node 1 (CCC) and Node 2 (CTT). While the tie component is used to determine the need for reinforcement.

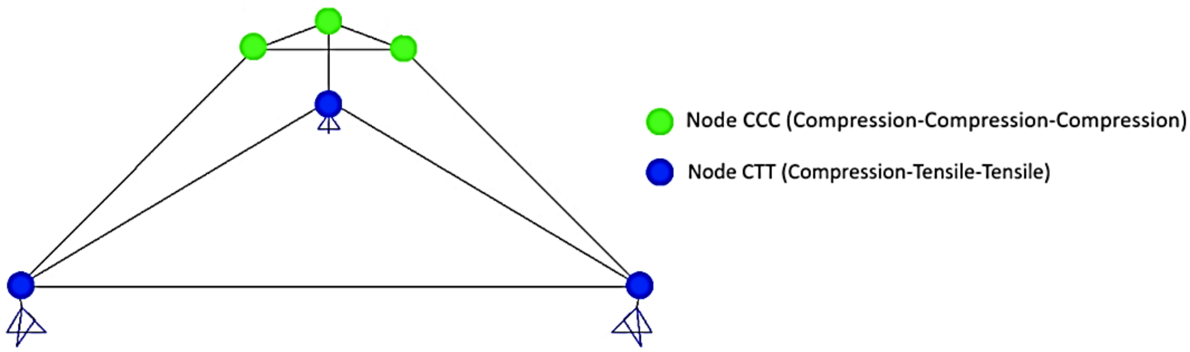

Figure 8: Node on STM Shape Modeling of Foundation Cap

Based on Figure 9, strength control was performed at the CTT (Compression-Tensile-Tensile) node zone by referring to equation (1) and equation (2).

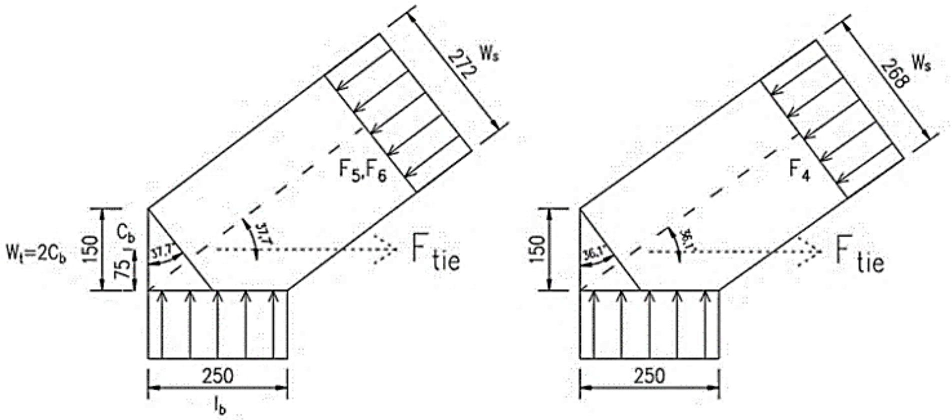

Figure 9: CTT Node Zone

Elements F_5 and F_6

W_t	= 2 x cover thickness = 150 mm
l_b	= 250 mm
Θ	= 37.7°
W_s	= l_b sinΘ + W_t cosΘ = 271.57 mm
β_s	= 0.75
f_{ns}	= f_{ce} x A_{cs}
	= β_s (0.85 f'$_c$) x W_s x l_b
	= 1077.69 kN
ϕf_{ns}	≥ f_{us}
808.27 MPa	≥ 421.85 MPa (**Ok**)

Element F_4

W_t	= 2 x cover thickness = 150 mm
l_b	= 250 mm
Θ	= 36.1°
W_s	= l_b sinΘ + W_t cosΘ = 268.50 mm
β_s	= 0.75
fns	= f_{ce} x A_{cs}
	= β_s (0.85 f'$_c$) x W_s x l_b
	= 1065.52 kN
ϕf_{ns}	≥ f_{us}
799.14 MPa	≥ 436.83 MPa (**Ok**)

Based on Figure 10, strength control is performed at the CCC (Compression-Compression-Compression) node zone by referring to equation (1) and equation (2).

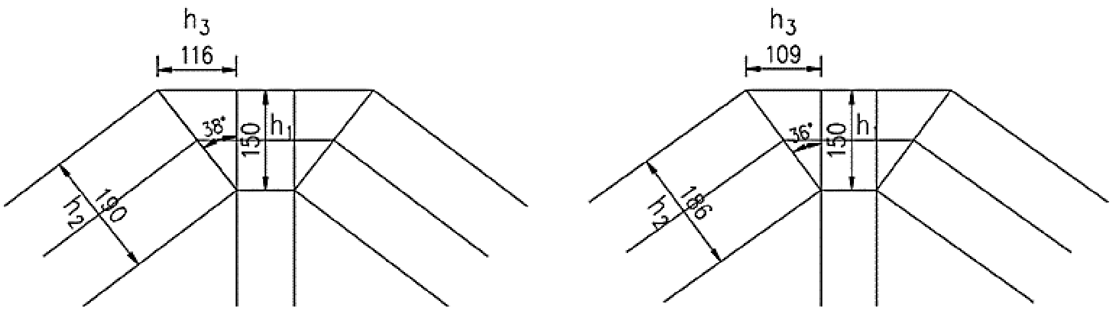

Figure 10: CCC Node Zone

θ	= 37,7°
h_1	= 2 x concrete cover = 150 mm
h_3	= 116 mm
h_2	= h_3 sinθ + h_1 cosθ = 189,62 mm
f_c	= $\frac{F_{us}\cos\theta}{h_1 x h_2}$ = 11,73 N/mm^2
β_s	= 1
f_{ce}	= 0,85 β_n f_c' = 21,17 N/mm^2
f_{ce}	≥ f_c
21,17 MPa	≥ 11,73 MPa (**Ok**)

θ	= 36,1°
h_1	= 2 x concrete cover = 150 mm
h_3	= 109 mm
h_2	= h_3 sinθ + h_1 cosθ = 185,42 mm
f_c	= $\frac{F_{us}\cos\theta}{h_1 x h_2}$ = 12,69 N/mm^2
β_s	= 1
f_{ce}	= 0,85 β_n f_c' = 21,17 N/mm^2
f_{ce}	≥ f_c
21,17 MPa	≥ 12,69 MPa (**Ok**)

ISSN 1412-2782 eISSN 2407-9103
Vol 23. No. 2 Mei 2024

Based on the above analysis, it is found that the nominal stress values at the CTT node and CCC node variations are much greater than the stresses that occur. So that the strut strength control of the node is safe.

G. Tie as flexural reinforcement

Ties are tensile elements in the strut and tie method that transmit tensile forces. In pile caps, ties consist of steel reinforcement that resists tensile forces resulting from load distribution. Ties must be properly connected to the struts at the node zone to ensure that tensile forces can be transferred without causing failure at the connection point. Calculation of reinforcement by referring to equation (3) and equation (4).

Element F_1

f_{ut} = 189,15 kN

A_{ts} ≥ 600,48 mm^2

Used Ø 16 mm reinforcement

$A_{s\ reinforcement} = \frac{1}{4}\pi D^2 = 201{,}06\ mm^2$

Rebars needed = $\frac{A_{ts}}{A_{s\ reinforcement}}$ = 2,99 ≈ 3 pieces

$A_{s\ install} \geq A_{ts}$

603,19 ≥ 600,48 (**Ok**)

3D16-60 reinforcement is used

Elements F_2 and F_3

f_{ut} = 200,01 kN

A_{ts} ≥ 634,95 mm^2

Used Ø 16 mm reinforcement

$A_{s\ reinforcement} = \frac{1}{4}\pi D^2 = 201{,}06\ mm^2$

Rebars needed = $\frac{A_{ts}}{A_{s\ reinforcement}}$ = 3,16 ≈ 4 pieces

$A_{s\ install} \geq A_{ts}$

804,25 ≥ 634,95 (**Ok**)

4D16-60 reinforcement is used

H. Comparison of STM Pile Cap Reinforcement with Conventional Methods

Based on the strut and tie model, the flexural reinforcement is triangular in shape following the tie element modeling line with the distance between reinforcements determined, while the conventional method of flexural reinforcement is installed by spreading the reinforcement evenly across the pile cap area. Comparison of pile cap reinforcement configuration with strut and tie model method and conventional method can be seen in Figures 11 to 12 and Table 3.

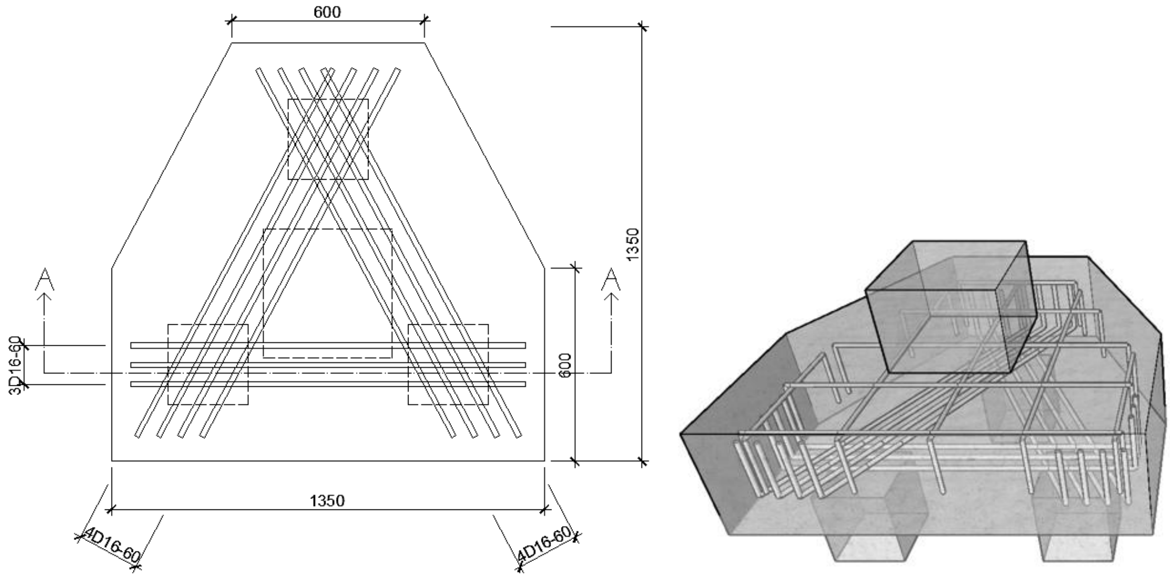

Figure 11: Pile Cap Flexural Reinforcement Configuration Strut and Tie Model Method

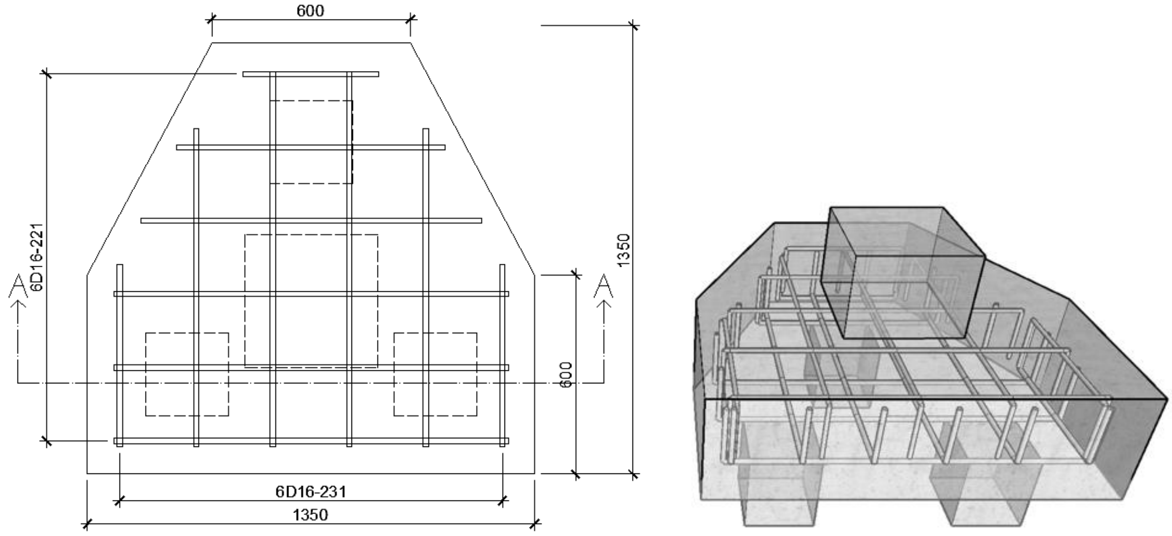

Figure 122: Pile Cap Flexural Reinforcement Configuration Conventional Method

TABLE III. FLEXURAL REINFORCEMENT OF STM AND CONVENTIONAL METHODS

Elements	n	D (mm)	Flexural Reinforcement Length (mm)	Description
1	3	16	18884	STM Method
2	4	16		
3	4	16		
X	6	16	16530	Conventional Method
Y	6	16		

Based on Table 3, the pile cap using the STM method has a total length of 18884 mm (12 D16). While the conventional method has a total length of 16530 mm (12 D16). This proves that the STM method produces more flexural reinforcement requirements by 14.24% compared to the conventional method. This is in line with the research [3] which found that the amount of reinforcement of the conventional method is less than that of the STM method in high beam structures. Based on research [19] from the comparison of conventional and STM methods, the difference in reinforcement area is 52%. However, in the strut and tie model method, it is found that it is easy to calculate the force and can analyze the flow of forces that occur so that the location of the reinforcement is exactly where it is needed so that the work function of the reinforcement becomes more effective.

The use of the STM Method in the design of reinforced concrete structures is sometimes under certain conditions considered more wasteful than conventional design methods. However, the STM method has a significant impact in the analysis and design of reinforced concrete. ACI 318 requires the use of the STM method to understand the force distribution in reinforced concrete elements, especially in discontinuity regions or regions with complex stress distributions. With STM, the force distribution in discontinuity regions (D-regions) is analyzed in more detail, reducing the risk of local failure and improving overall safety. This is in line with research [2], that with the same design load but the STM method has a greater load capacity when compared to the conventional method. This is evidenced by the increase in the yield condition load capacity to the design load on the STM method pile cap test specimen by 32.2%, while in the conventional method it is 9.3%. Furthermore, Yun and Lee (2021) stated that STM helps ensure structural safety by designing elements such as corbels, which often fail if not designed properly [20].

Conclusions

Based on the analysis and discussion, there are several conclusions from this research, including:

1. Comparison of pile cap reinforcement configuration using STM method with conventional method is visualized in the form of reinforcement detail drawing. The STM method consists of element 1 (3D16), element 2 (4D16), and element 3 (4D16), while the conventional method consists of X direction (6D16) and Y direction (6D16).
2. The STM method has increased the flexural reinforcement requirement by 14.24% compared to the conventional method. The total length of flexural reinforcement required for the STM method is 18884 mm (and the conventional method is 16530 mm).

References

[1] T. A. Putera, M. H. Gultom, and F. P. Susanto, "Evaluasi Dan Perencanaan *Pile Cap* Pada Fly Over Jamin Ginting Kota Medan," *PORTAL J. Tek. Sipil*, vol. 11, no. 2, pp. 30–37, 2019.

[2] Sukarman, D. Sulistyo, and I. S. Irawati, "Analisis Regangan Baja Tulangan Pada Struktur *Pile Cap* Empat Tiang Metode *Strut and Tie Model*," vol. XV, no. 2, 2019.

[3] N. Luthfiana and Y. A. Priastiwi, "Analisis Alternatif Dalam Merancang Balok Tinggi Menggunakan *Strut and Tie Model*," vol. 11, no. 1, pp. 89–102, 2021.

[4] A. Raj and M. G. Airin, "*Experimental And Analytical Investigation Of Strut and Tie Model Method Of Pile Cap*," pp. 30–35, 2017.

[5] M. A. Sedayu, D. Sulistyo, and A. Aminullah, "Eksperimen Pada Struktur *Pile Cap* Tiga Tiang Dengan Metode *Strut and Tie Model*," *INERSIA lNformasi dan Ekspose Has. Ris. Tek. SIpil dan Arsit.*, vol. 15, no. 2, pp. 31–43, 2019.

[6] I. R. S. Misbakhul Munir, Zulfikar Djauhari, "Analisa Balok Tinggi Beton Bertulang Dengan Menggunakan Metode *Strut and Tie Model*," *Jom FTEKNIK*, vol. 1, pp. 1–15, 2014.

[7] P. Setianugroho, A. Rosyidah, and J. Saputra, "Kinerja Bangunan Tahan Gempa Dengan Balok Tinggi Metode *Strut and Tie* Berdasarkan SNI 2847-2019 dan ACI 318-19," no. 28, 2022.

[8] V. V. Nori and M. S. Tharval, "*Design of Pile Caps - Strut and tie Model Method*," *Indian Concr. J.*, vol. 81, no. 4, pp. 13–19, 2007.

[9] H. Hardjasaputra, Perancangan Beton Struktural Berdasarkan Model Strat dan Pengikat (*Strut-and-Tie Model*) SNI 2847-2013. Jakarta: Universitas Pelita Harapan, 2016.

[10] H. Hardjasaputra and S. Tumilar, Model Penunjang dan Pengikat (*Strut–and–Tie Model*) Pada Perancangan Struktur Beton. Jakarta: Universitas Pelita Harapan, 2002.

[11] BSNP, Persyaratan Beton Struktural Untuk Bangunan Gedung Dan Penjelasan *(SNI 2847:2019)*. 2019.

[12] R. Simalango, "Analisa dan Perencanaan *Pile Cap* Dengan Metode *Strut and Tie Model* Berdasarkan ACI *Building* Code 318-2002," pp. 138–155, 2011.

[13] D. Mitchell, M. P. B. Collins, S. B., and R. B. G, *AASHTO LRFD Strut and-Tie Model Design Examples*. Portland Cement Association.

[14] W. C. Teng, *Foundation Design*. Englewood Cliffs, New Jersey: Prentice- Hall., 1969.

[15] K. H. Reineck, "*Modeling Structural Concrete with Strut-and-Tie Models - Summarizing Discussion of the Examples as per Appendix A of* ACI 318 - 2002," *American Concrete Institute, ACI Special Publication*, vol. SP-208. 2002.

[16] J. W. Park, D. Kuchma, and R. Souza, "*Strength Predictions of Pile Caps by a Strut-and-Tie Model Approach*," *Can. J. Civ. Eng.*, vol. 35, no. 12, pp. 1399–1413, 2008.

[17] D. D. Saputro and H. Koco Buwono, "Studi Pengaruh Jarak Tiang Pancang Pada Kelompok Tiang Terhadap Perubahan Dimensi *Pile Cap*," *Konstruksia*, vol. 5, no. 1, pp. 85–93, 2013.

[18] P. G. Taufik, D. Sulistyo, and A. Aminullah, "Perilaku Struktur *Pile Cap* 3 Tiang Dengan Beban Eksentris Yang Dirancang Menggunakan *Strut and Tie Model* Dengan Metode Numerik," *J. Media Tek. Sipil*, vol. 17, no. 1, pp. 51–63, 2019.

[19] I. N. Iskandar, "Analisis *Pile Cap* dengan Metode *Strut and Tie* Pada Pembangunan Infrastruktur di Kota Sukabumi," *J. Penelit. Pendidik. Guru Sekol. Dasar*, vol. 6, no. August, p. 128, 2019.

[20] Yun. Y. M, and Lee. Y, "Strengths of Struts and Node Zones for Strut-and-Tie Model Design of Reinforced Concrete Corbels" Civile Journal, vol. 7, no. 08 August, p. 1275-1289, 2021.